CHAPTER ELEVEN

Basic Emitter-Coupled Logic [ECL]

Digital Electronics.

Introduction

Emitter-Coupled Logic (ECL) (Analogous to the analog difference amplifier)

The BJTs in ECL circuits do not operate in saturation mode, but either in cut-off or forward-active modes

The ECL circuits are the fastest switching time of commercially digital circuits.

Typical propagation delay times are on the order of 1ns, allowing for clock frequencies up to 1GHz.

However, ECL circuits have the highest power dissipation of all logic families, typically 25mW per gate.

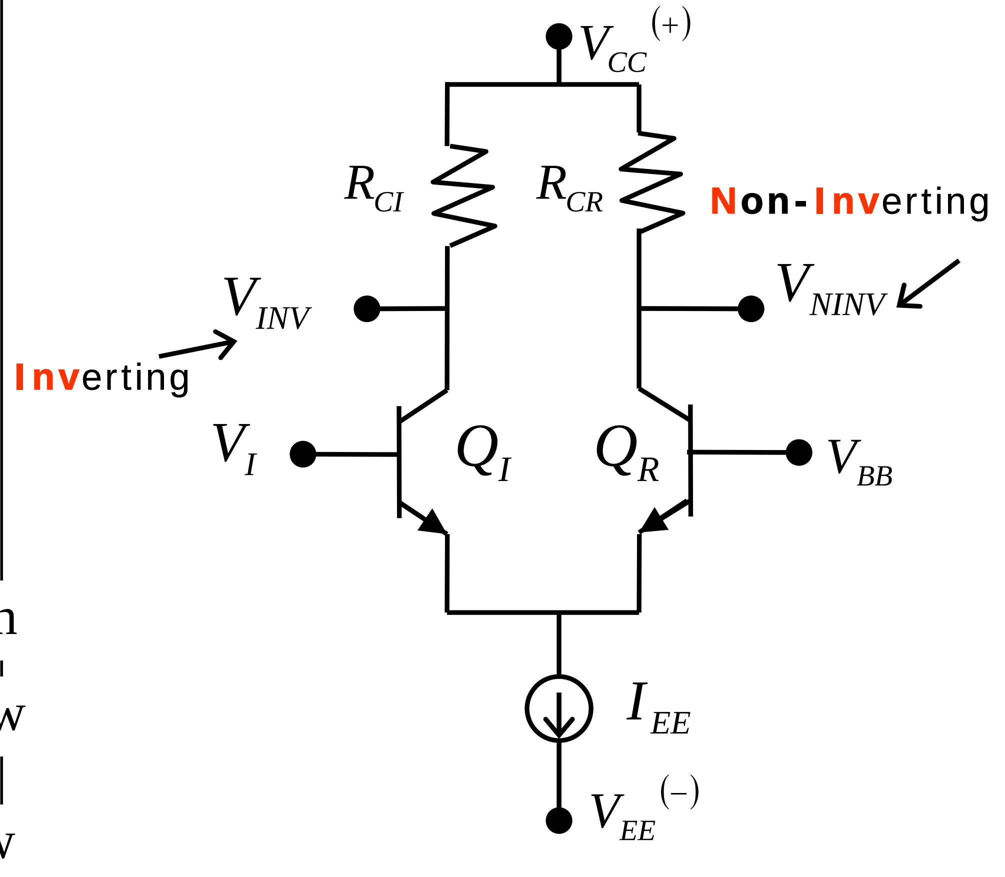
BJT Current Switch

This figure shows an ideal BJT current switch

The input is at the base of Q_I , and V_{BB} is a constant reference voltage

The coupled emitters are ideally connected to a constant current source I_{EE}.

Basic ECL current switch



$V_I < V_{BB} \Rightarrow Q_I$ is OFF $\Rightarrow V_{INV}$ is High

Q_R is FA $\Rightarrow V_{NINV}$ is Low

$V_I > V_{BB} \Rightarrow Q_I$ is FA $\Rightarrow V_{INV}$ is Low

Q_R is OFF $\Rightarrow V_{NINV}$ is High

BJT Current Switch

This figure shows an early ECL implementation

$$I_{RE} = \frac{V_E - V_{EE}}{R_E}$$

Outputs are taken at the collectors of Q_I and Q_R.

$$V_{O,1} = V_{INV} = V_{C,I} = V_{CC} - I_{C,I} R_{CI}$$

and

$$V_{O,2} = V_{NINV} = V_{C,R} = V_{CC} - I_{C,R} R_{CR}$$

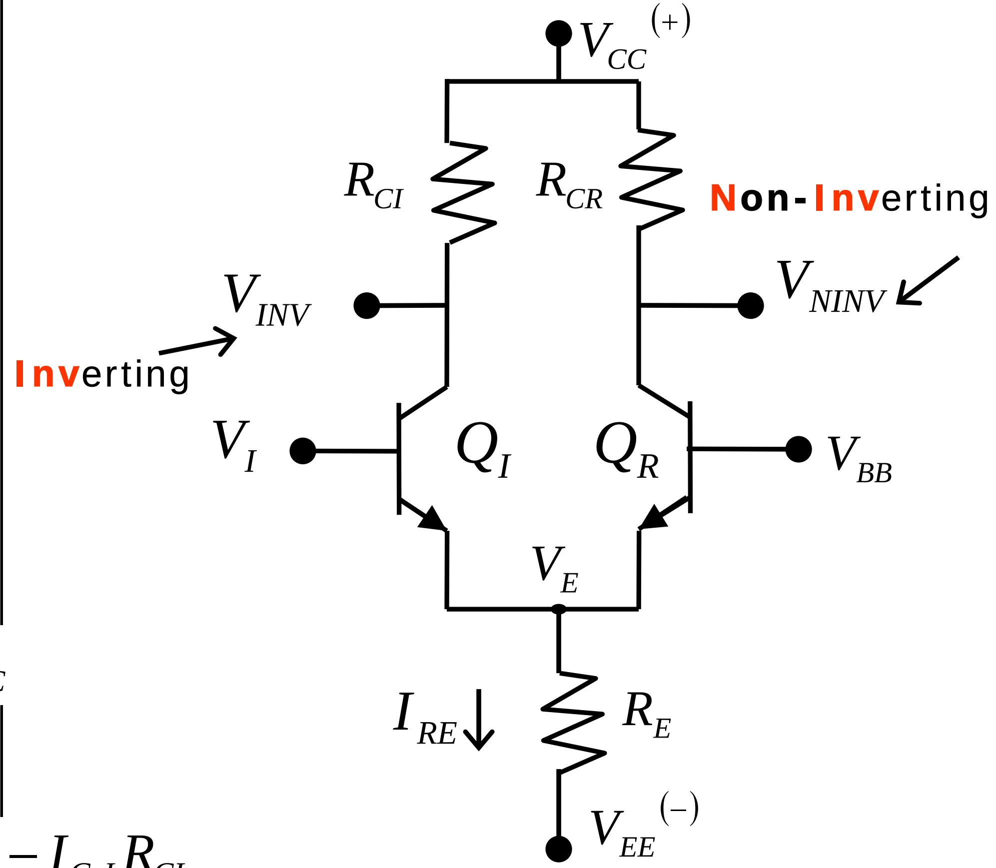
$V_I < V_{BB} \Rightarrow Q_I$ is OFF $\Rightarrow$ $V_{INV} = V_{CC}$

$$V_{NINV} = V_{CC} - I_{C,R} R_{CR}$$

$V_I > V_{BB} \Rightarrow Q_I$ is FA $\Rightarrow$ $V_{INV} = V_{CC} - I_{C,I} R_{CI}$

$$V_{NINV} = V_{CC}$$

Resistor ECL current switch



Voltage Transfer Characteristics of ECL Current Switch

Output High Voltage

$\underline{V_{OH}}$

For $V_I < V_{BB}$, Q_I is off, Q_R is in the forward-active mode

Proof: with Q_R F.A.:

$$V_E = V_{BB} - V_{BE,R}(ECL)$$

and

$$V_{BE,I} = V_I - V_E = V_I - V_{BB} + V_{BE,R}(ECL)$$

$V_I - V_{BB} < 0$

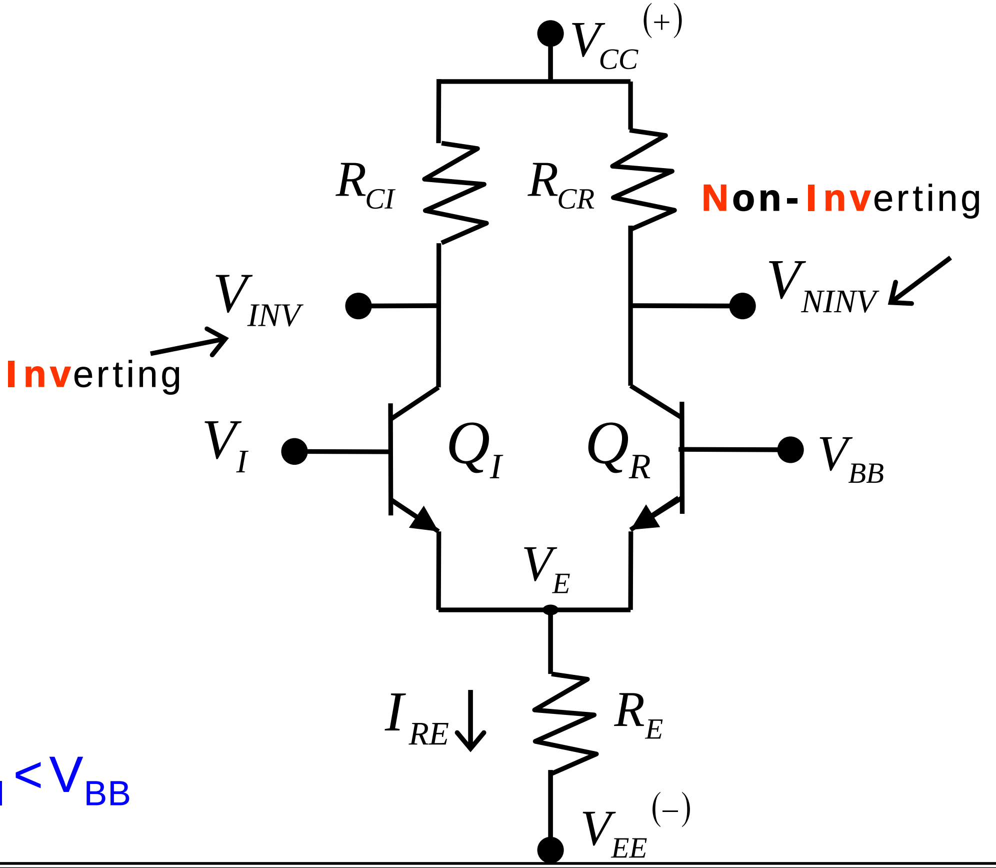
For $V_I < V_{BB}$ (Low),

Q_I is off, i.e. $I_{C,I} = 0$

$V_{BE,I} < V_{BE}(ECL)$

$\boxed{V_{BE}(ECL) = 0.75V}$

Resistor ECL current switch



$$V_{INV} = V_{OH} = V_{CC}$$

Voltage Transfer Characteristics of ECL Current Switch

Threshold Voltage

V_{TH}

For $V_I = V_{BB}$, both Q_I and Q_R are in the forward-active mode ($V_{BE,I} = V_{BE,R}$)

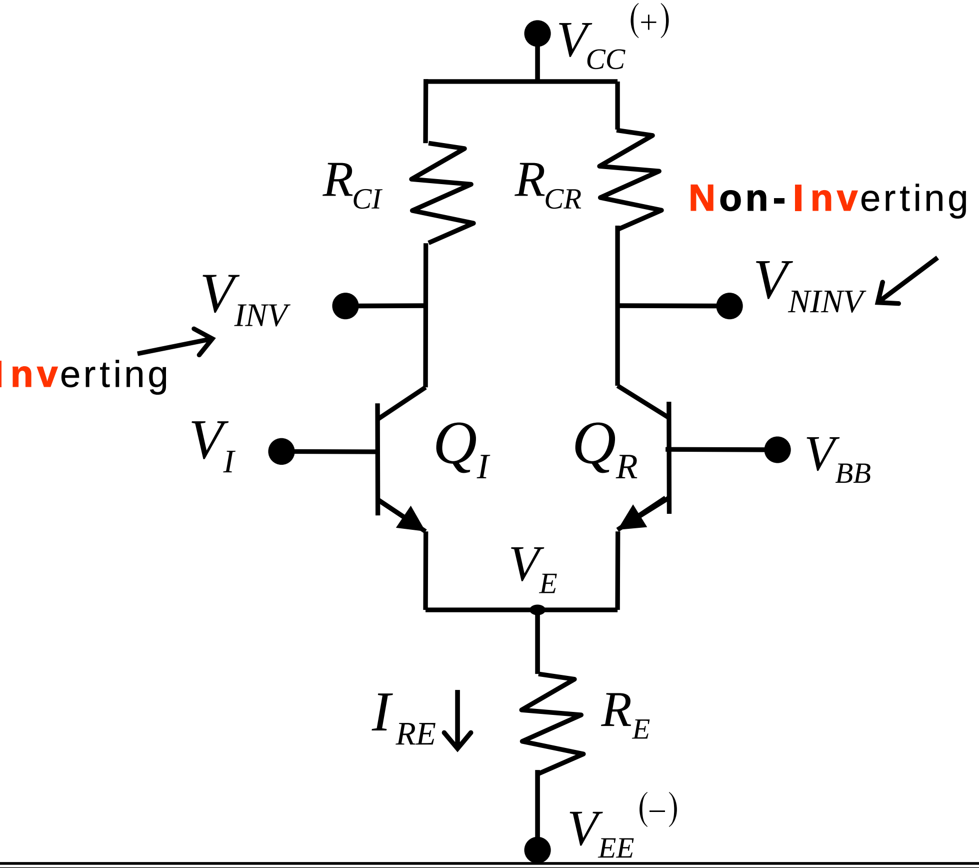
$$I_{C,I} = I_{C,R} = \frac{I_{RE}}{2} \quad \left(\text{assuming}\right) \; (\beta_F >> 1)$$

and

$$V_{INV} = V_{CC} - \frac{I_{RE}}{2} R_{CI}$$

$$V_{TH} = V_{BB}$$

Resistor ECL current switch



Voltage Transfer Characteristics of ECL Current Switch

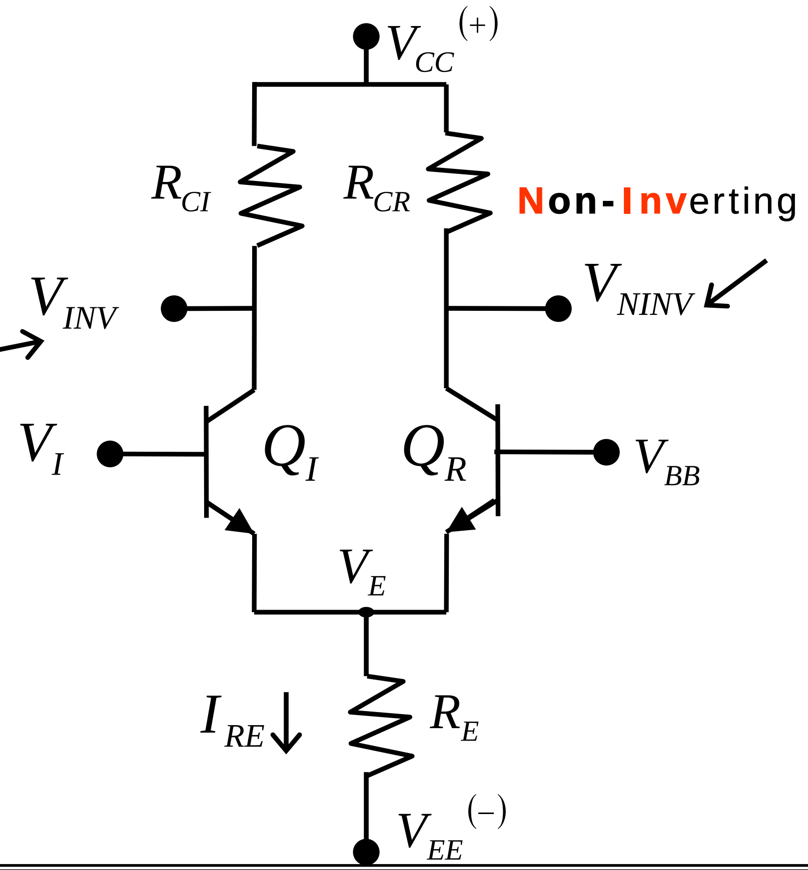
Input high and low Voltages

$\underline{V_{IH}}$ $\underline{V_{IL}}$

For V_I is slightly less than V_{BB}, Q_I is forward-active mode BUT not conducting as heavily as Q_R.

For V_I is slightly greater than V_{BB}, Q_R is forward-active mode BUT not conducting as heavily as Q_I.

Resistor ECL current switch



Experimentally, the transition width is found to be about $V_{TW}=0.1V$ and centered around $V_I=V_{BB}$

$$V_{IL} = V_{BB} - 0.05 \quad \& \quad V_{IH} = V_{BB} + 0.05$$

Voltage Transfer Characteristics of ECL Current Switch

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Output low Voltage

$\underline{V_{OL}}$

For $V_I > V_{BB}$, Q_I begins to conduct.

$$V_E = V_I - V_{BE,I}(ECL)$$

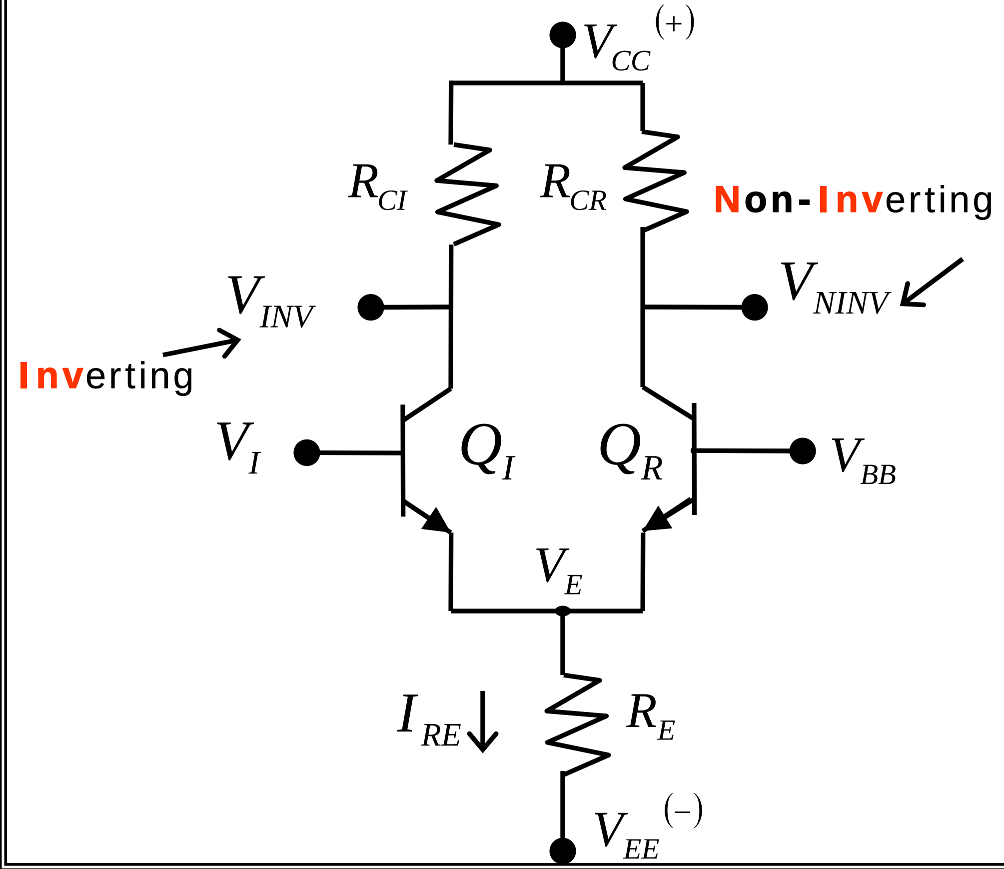
$$V_{INV} = V_{CC} - I_{C,I}R_{CI}$$

As V_I increases, V_E also increases, while $V_{B,R}=V_{BB}$ (fixed)

Thus, raising V_I by 0.05V beyond V_{BB}, $V_{BE,R}$ sufficiently decreases to cut-off Q_R

The input voltage which turns Q_R off is $V_I=V_{IH}$ resulting in $V_O=V_{OL}$.

Resistor ECL current switch



$$I_{C,I} \approx I_{RE} = \frac{V_E - V_{EE}}{R_E} = \frac{V_I - V_{BE,I}(ECL) - V_{EE}}{R_E}$$

Voltage Transfer Characteristics of ECL Current Switch

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Output low Voltage

$\underline{V_{OL}}$

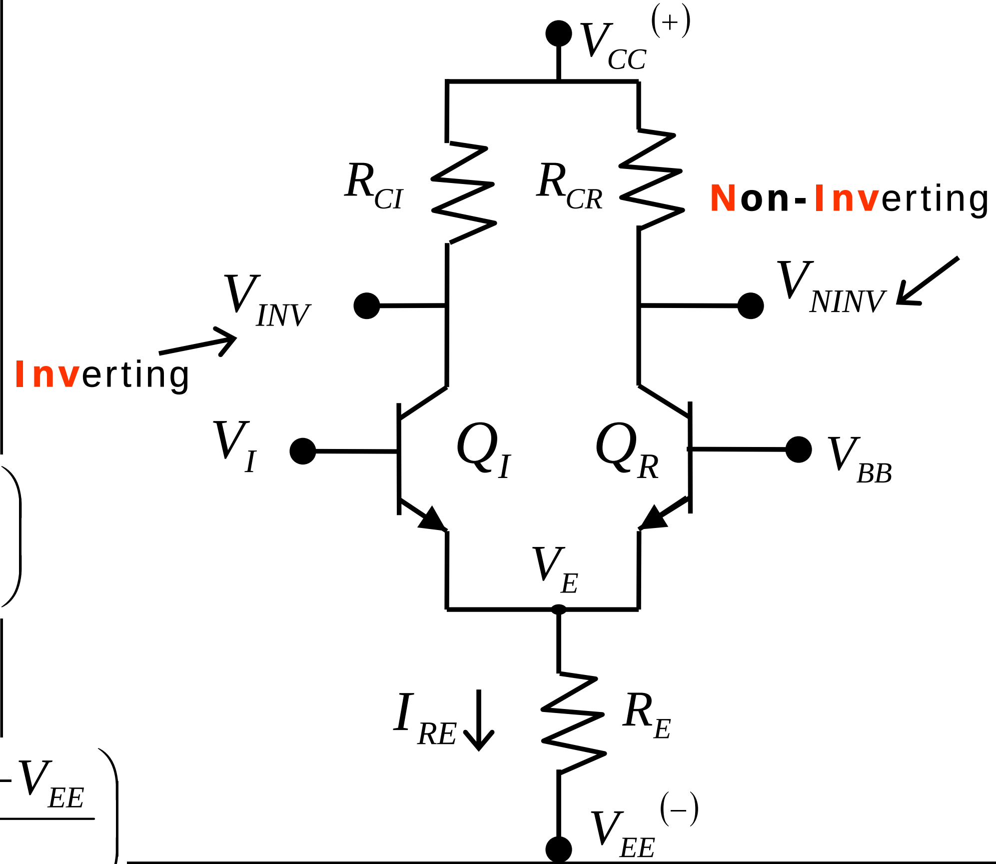
$$V_{INV} = V_{CC} - I_{C,I} R_{CI}$$

$$V_{INV} = V_{CC} - R_{CI}\left(\frac{V_I - V_{BE,I}(ECL) - V_{EE}}{R_E}\right)$$

$$V_{INV} = V_{CC} - R_{CI}\left(\frac{V_{IH} - V_{BE,I}(ECL) - V_{EE}}{R_E}\right)$$

$$= V_{OL}$$

Resistor ECL current switch



Voltage Transfer Characteristics of ECL Current Switch

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VTC beyond V_{IH}

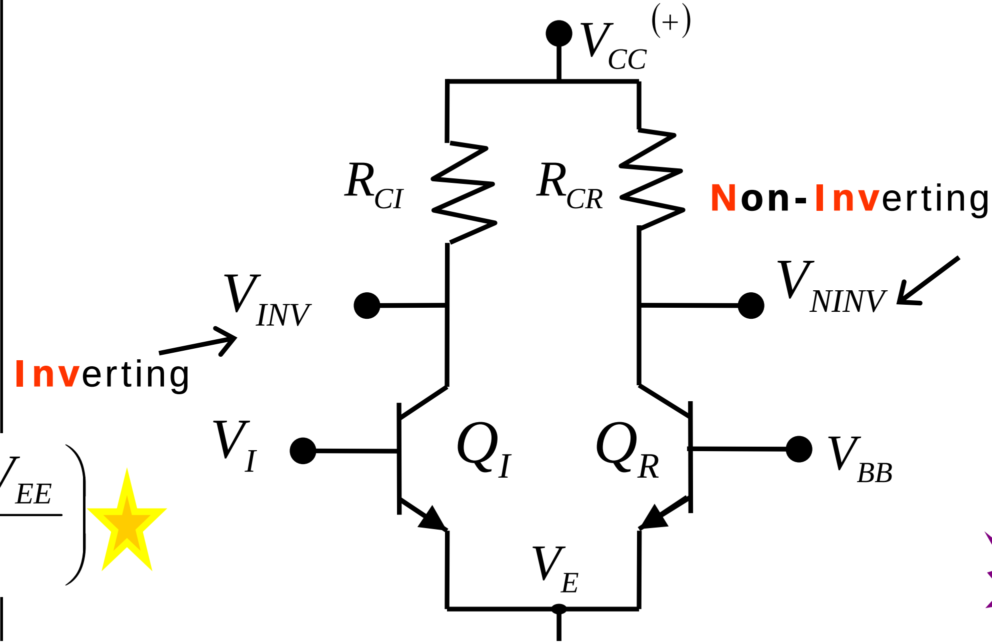
As V_I increases beyond V_{IH}

$$I_{C,I} = \frac{V_I - V_{BE,I}(ECL) - V_{EE}}{R_E}$$

The output voltage V_O decreases linearly with V_I

$$V_{INV} = V_{CC} - R_{CI}\left(\frac{V_I - V_{BE,I}(ECL) - V_{EE}}{R_E}\right)$$

Resistor ECL current switch



Q_I will eventually saturate with further increase of V_I if:

$$V_{INV} = V_I - V_{BC}(sat)$$

Saturation voltage

$$V_S = V_I = \left(\frac{V_{CC} + V_{BC,I}(sat) + \left(V_{BE,I}(sat) + V_{EE}\right)\frac{R_{C,I}}{R_E}}{1 + \frac{R_{C,I}}{R_E}}\right)$$

This region of saturation is avoided

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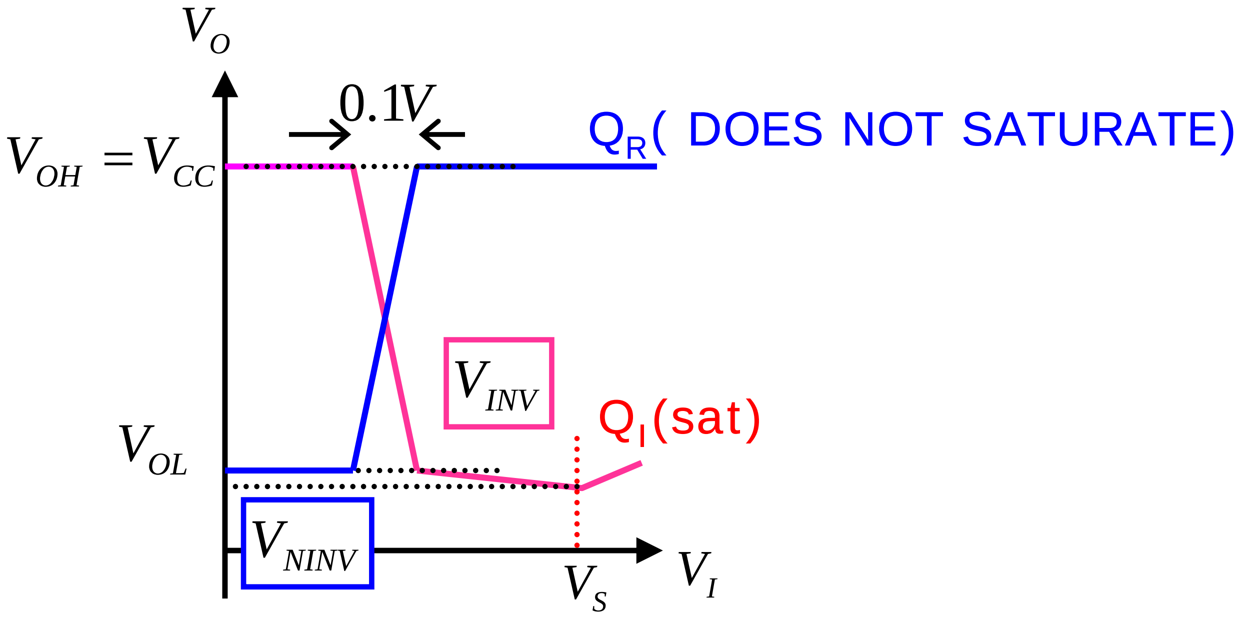
Voltage Transfer Characteristics of ECL Current Switch



Voltage Transfer Characteristics of ECL Current Switch

- Example

Calculate the critical values of the VTC of VI for ECL current switch shown previously assuming:

$V_{EE}=0V$, $V_{BB}=2.6V$, $V_{BE}(ECL)=0.75V$, $V_{BC}(sat)=0.6V$

$V_{CC}=5V$, $R_{CI}=R_{CR}=R_E=1k\Omega$,

- Solution

$$\boxed{V_{OH}=V_{CC}=5V}$$

$$\boxed{V_{IL}=V_{BB}-0.05=2.55V}$$

$$\boxed{V_{IH}=V_{BB}+0.05=2.65V}$$

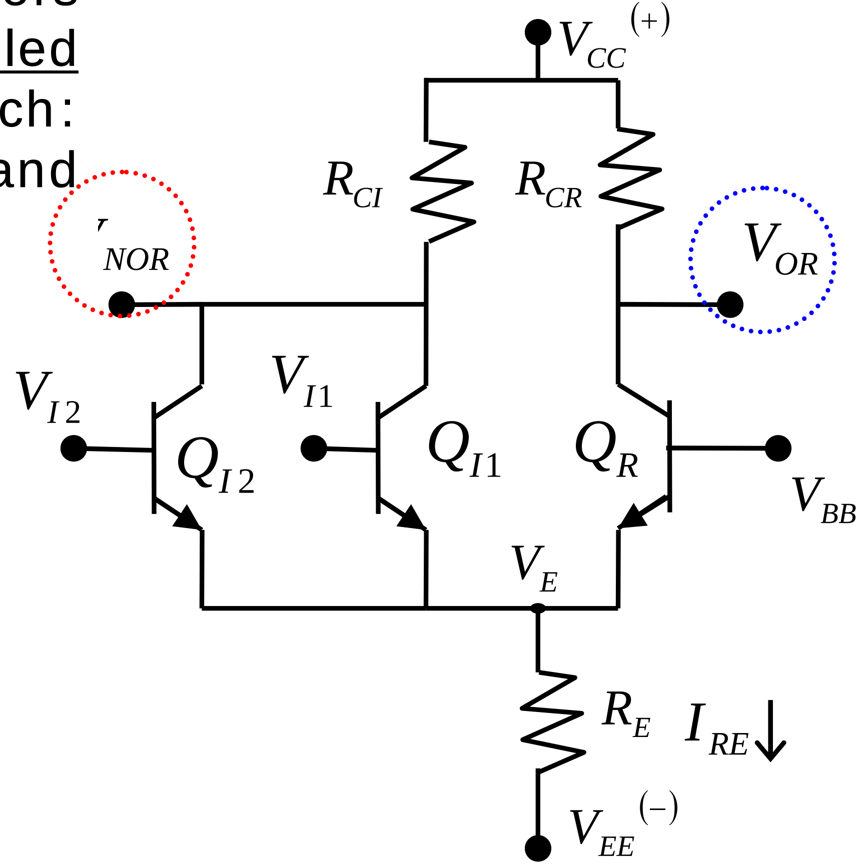
$$\boxed{V_{OL}=V_{CC}-R_{CI}\left(\frac{V_{IH}-V_{BE,I}(ECL)-V_{EE}}{R_E}\right)=3.10V}$$

$$\boxed{V_S=\left(\frac{V_{CC}+V_{BC,I}(sat)+\left(V_{BE,I}(ECL)+V_{EE}\right)\frac{R_{C,I}}{R_E}}{1+\frac{R_{C,I}}{R_E}}\right)=3.2V}$$

$$\boxed{V_{INV}(V_I=V_S)=V_S-V_{BC,I}(sat)=2.6V}$$

Basic ECL NOR/OR Gate

Adding additional input transistors with coupled collectors and coupled emitters to the ECL current switch: V_{INV} becomes NOR output and V_{NINV} becomes OR output.



For any high-state input, the corresponding transistor is forward-active and then the corresponding collector current flows through R_{CI} and

$$\boxed{V_{NOR} = V_{INV} = V_{CC} - I_{C,I} R_{CI} \ (Low)}$$

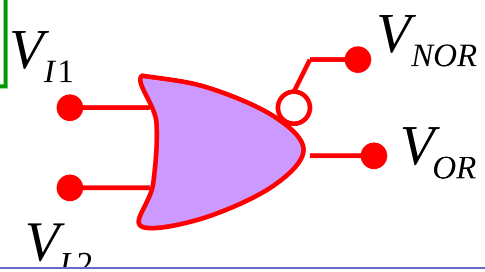
$$\boxed{V_{OR} = V_{NINV} = V_{CC} \ (High)}$$

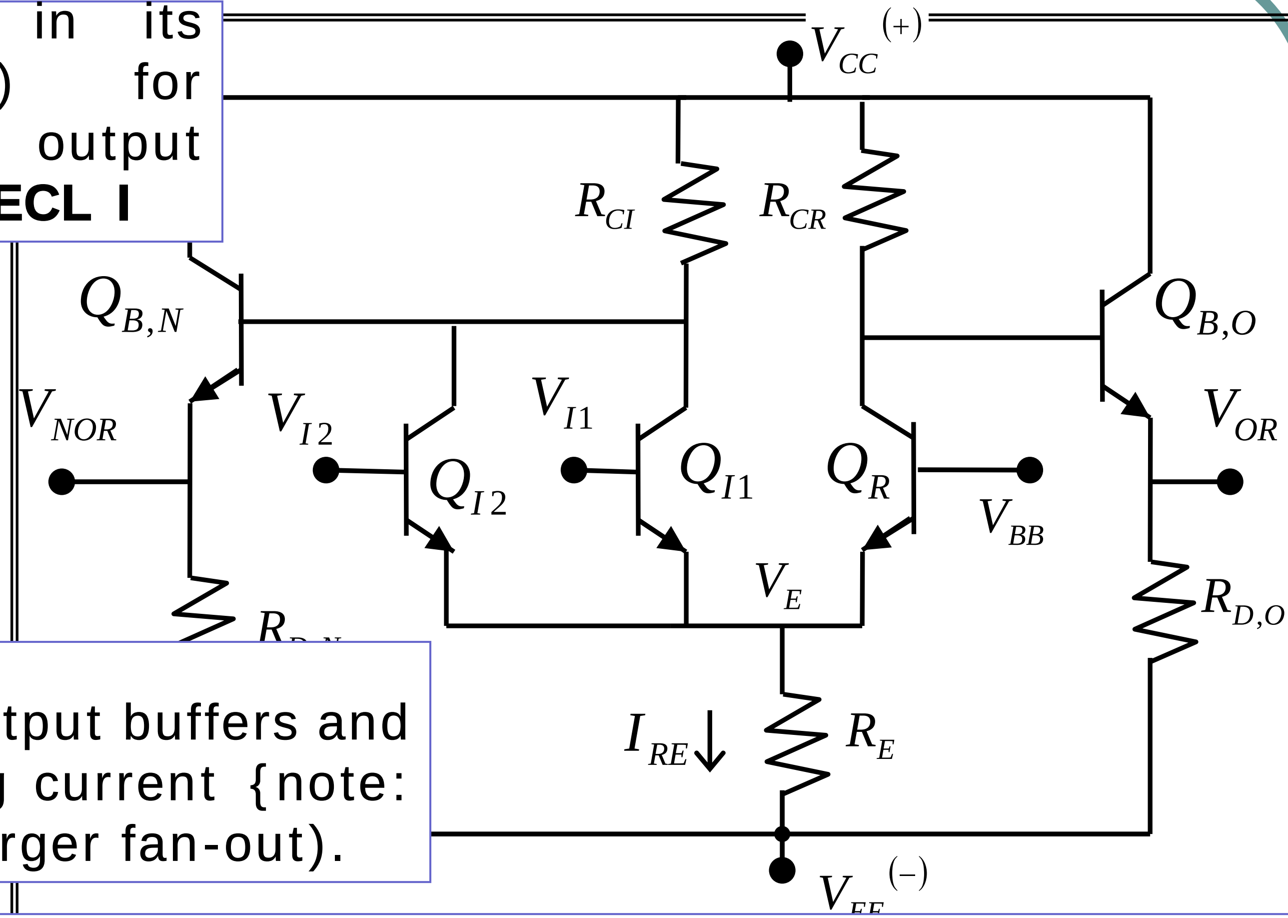
If all inputs are low, then all the corresponding transistors are cut-off and then

$$\boxed{V_{NOR} = V_{INV} = V_{CC} \ (High)} \quad \boxed{V_{OR} = V_{NINV} = V_{CC} - I_{C,R} R_{CR} \ (Low)}$$

MECL I NOR/OR Gate with Output Buffer

First ECL gate in its (NOR/OR form) for Motorola using output buffers is called **MECL I**





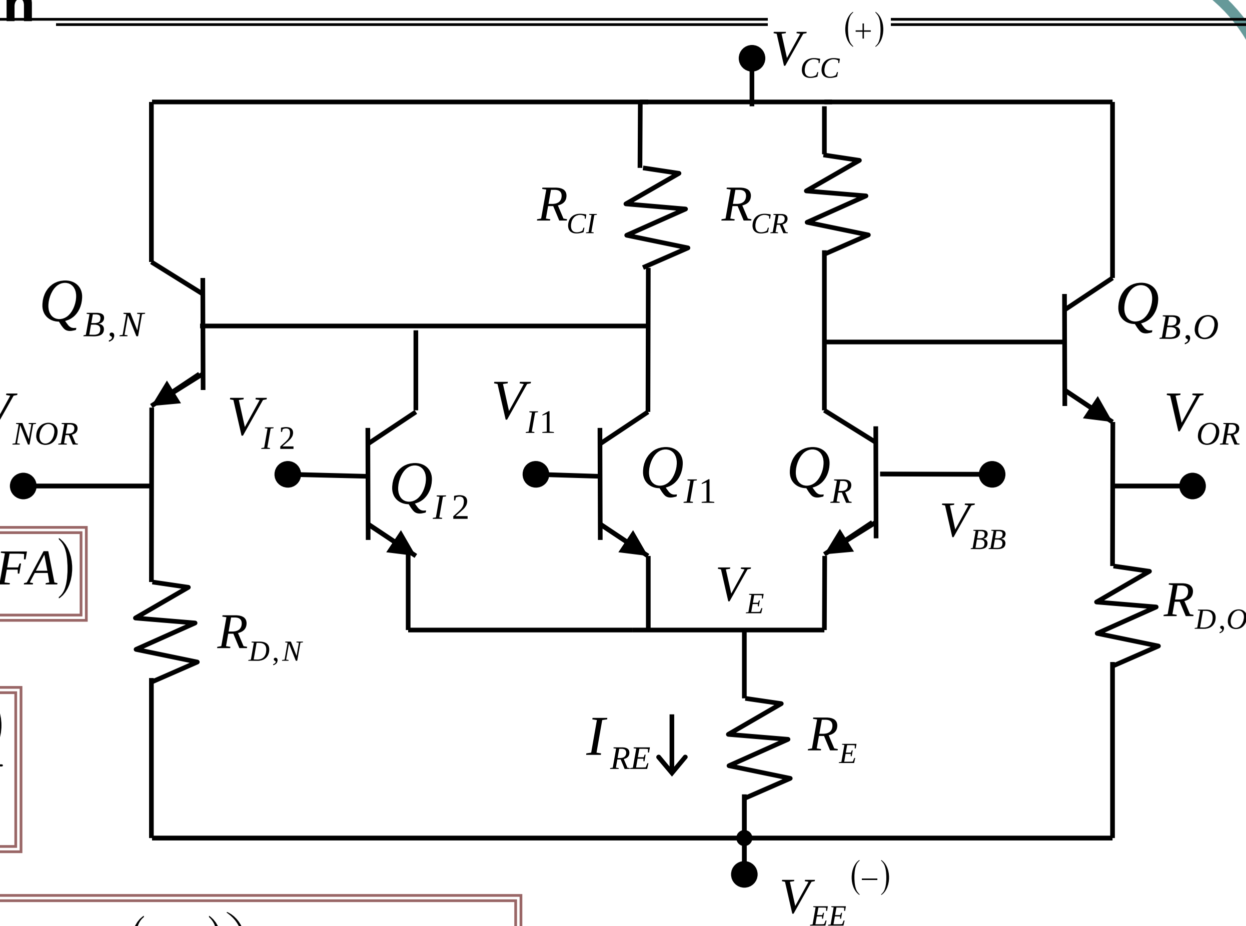
- $Q_{B,N}$ and $Q_{B,O}$ are output buffers and provide large sourcing current {note: $V_C > V_B$} to the load (larger fan-out).

- $Q_{B,N}$ and $Q_{B,O}$ also provide voltage level shift by V_{BE}(ECL) resulting in an output voltage swing in a range compatible with the input voltage swing

VTC of MECL I NOR/OR Gate with Output Buffer

Output High Voltage $\underline{V_{OH}}$

When all inputs are low; V_I's are low, Q_I's are cut-off



$$V_{NOR} = V_{CC} - R_{CI} I_{B,BN} - V_{BE,BN}(FA)$$

$$I_{B,BN} = \frac{V_{CC} - V_{EE} - V_{BE,BN}(FA)}{R_{CI} + (1+\beta_F) R_{D,N}}$$

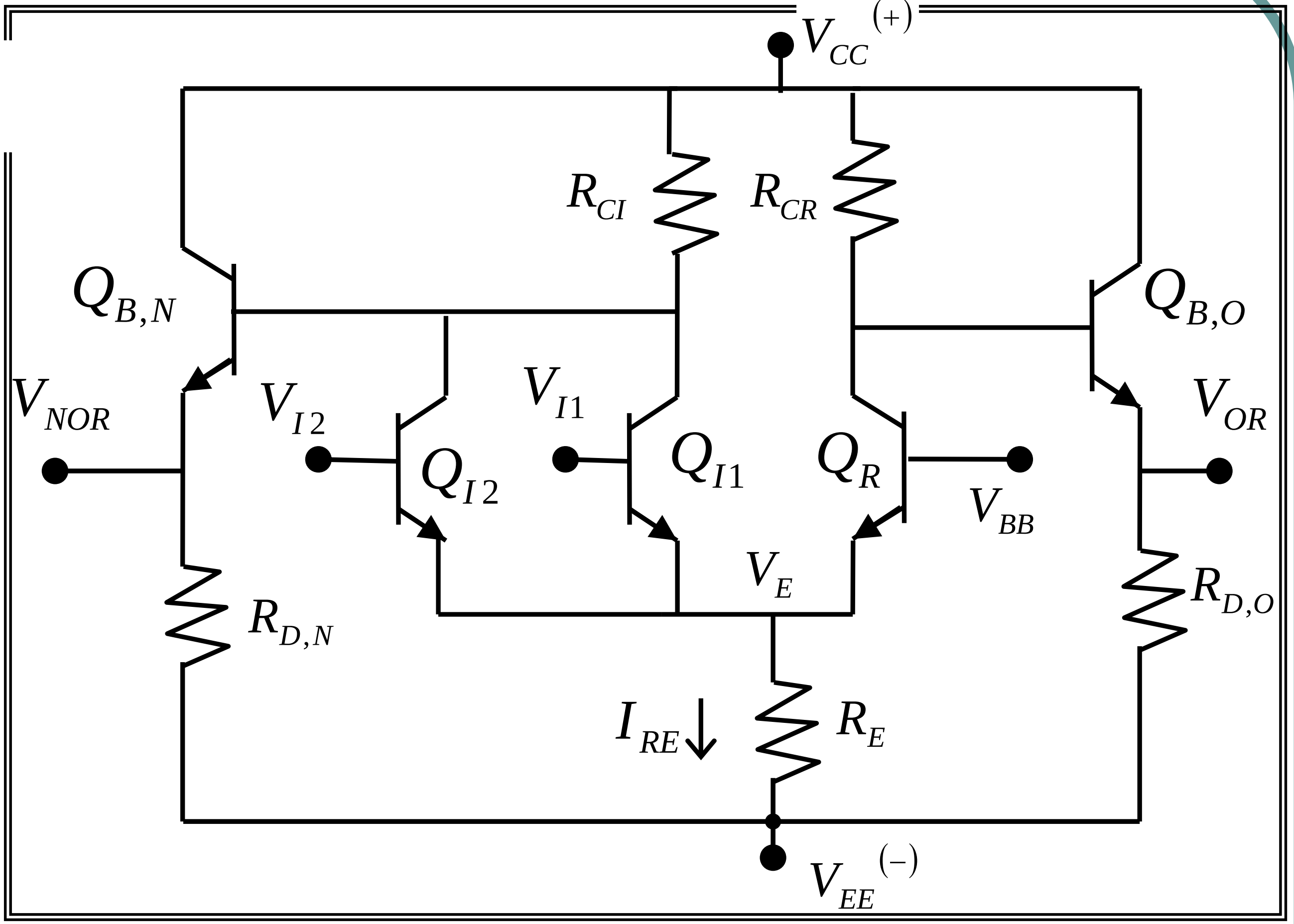
$$V_{OH} = V_{CC} - R_{CI}\left(\frac{V_{CC} - V_{EE} - V_{BE,BN}(FA)}{R_{CI} + (1+\beta_F) R_{D,N}}\right) - V_{BE,BN}(FA)$$

Input Low and High Voltages

V_{IL} ___ V_{IH} ___

$$\boxed{V_{IL} = V_{BB} - 0.05}$$

$$\boxed{V_{IH} = V_{BB} + 0.05}$$



VTC of MECL I NOR/OR Gate with Output Buffer

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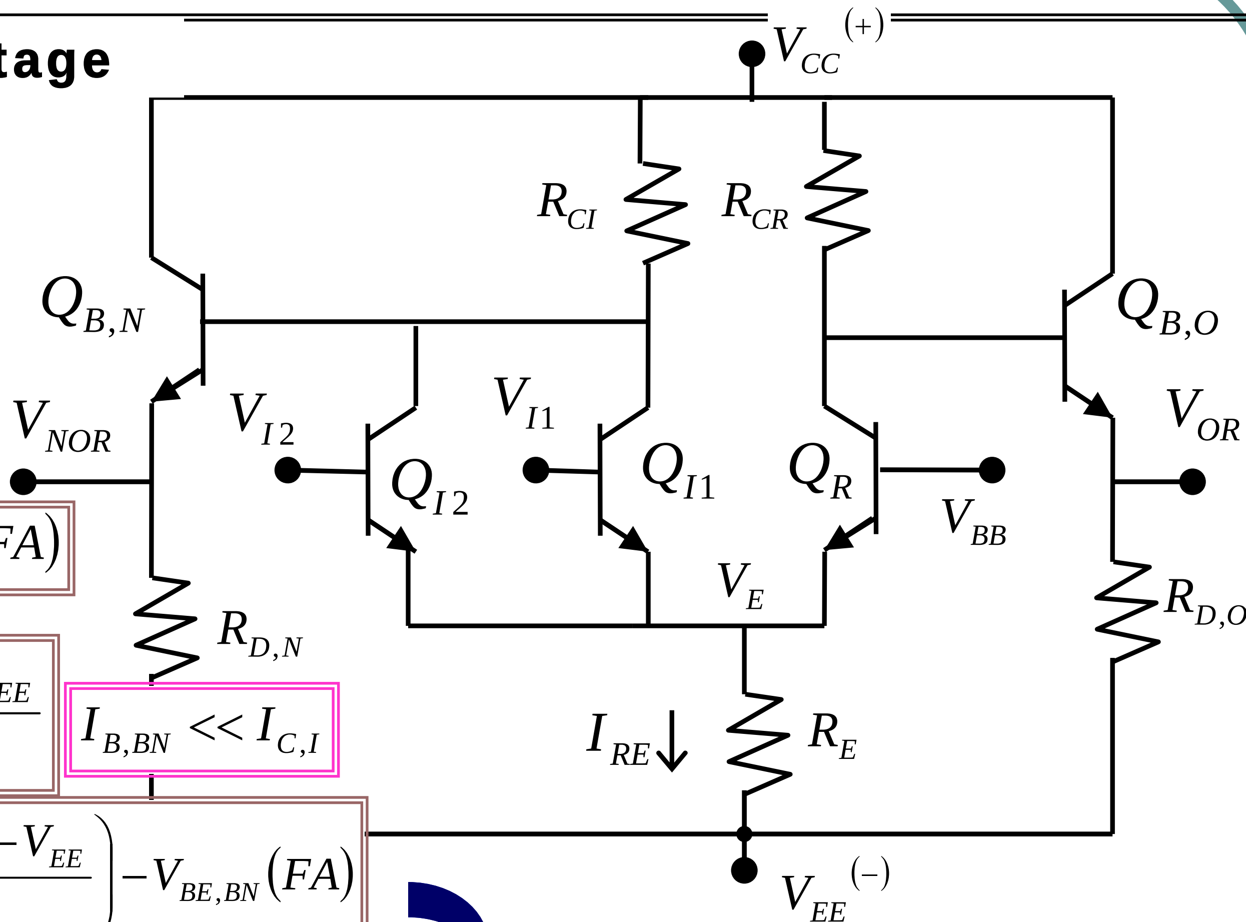
Output Low Voltage

$\underline{V_{OL}}$

If one input is high; V_I is high, Q_I is forward-active



$$V_{NOR} = V_{CC} - R_{CI} I_{C,I} - V_{BE,BN}(FA)$$

$$I_{C,I} \approx I_{E,I} = \frac{V_I - V_{BE,I}(ECL) - V_{EE}}{R_E}$$

$$I_{B,BN} << I_{C,I}$$

$$V_{NOR} = V_{CC} - R_{CI}\left(\frac{V_I - V_{BE,I}(ECL) - V_{EE}}{R_E}\right) - V_{BE,BN}(FA)$$

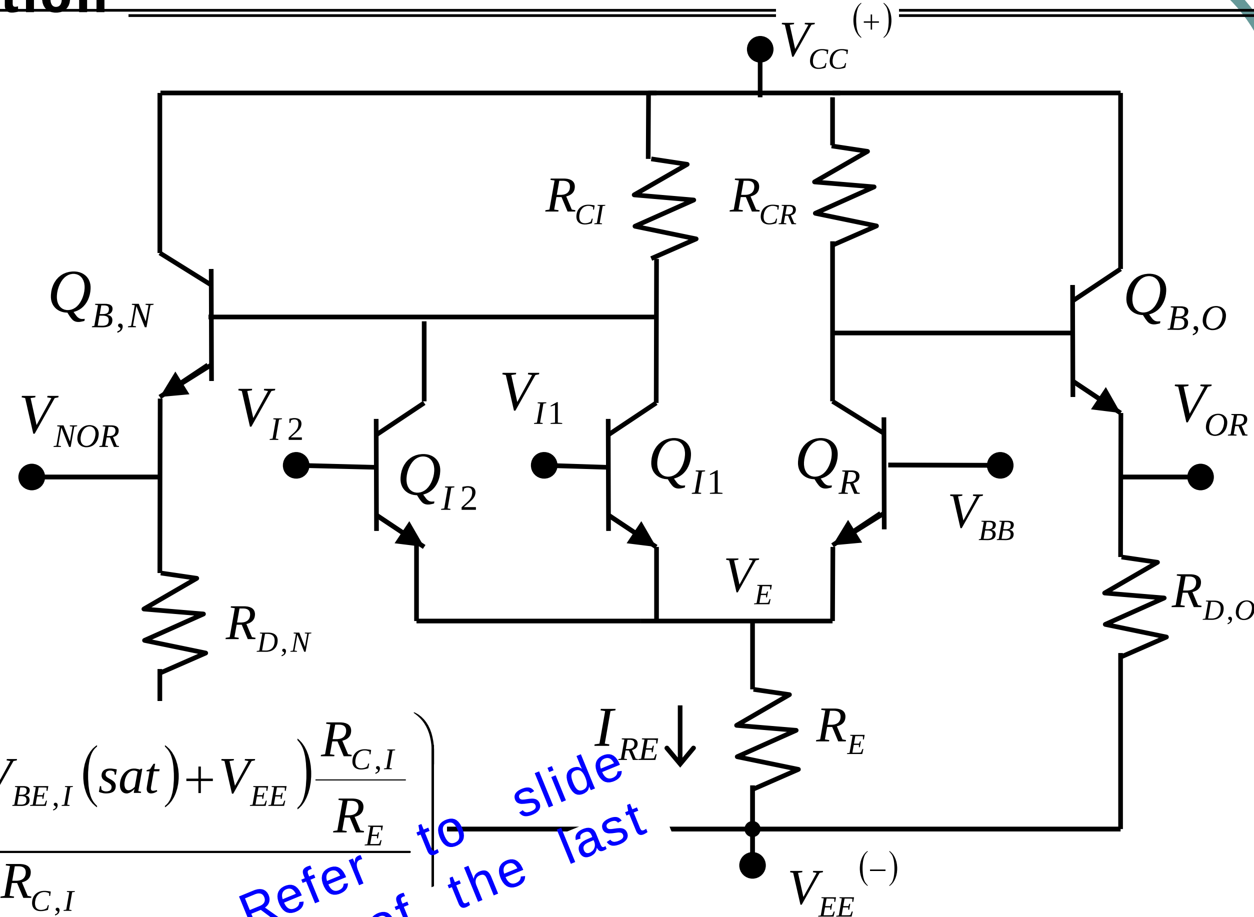
$$V_{OL} = V_{CC} - R_{CI}\left(\frac{V_{IH} - V_{BE,I}(ECL) - V_{EE}}{R_E}\right) - V_{BE,BN}(FA)$$

VTC of MECL I NOR/OR Gate with Output Buffer

V_{NOR} Region **Saturation**

As V_I increases beyond V_{IH}

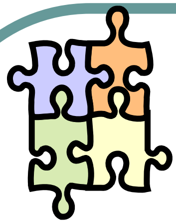
$$V_S > V_{IH}$$



$$V_S = V_I = \left(\frac{V_{CC} + V_{BC,I}(sat) + \left(V_{BE,I}(sat) + V_{EE}\right)\frac{R_{C,I}}{R_E}}{1 + \frac{R_{C,I}}{R_E}} \right)$$

Refer to slide 10 of the last lecture

VTC of MECL I NOR/OR Gate with Output Buffer



- Example

Calculate the critical values of the VTC of V_I for MECL I circuit shown previously assuming:

V_{EE}=-5.2V, V_{BB}=-1.175 V, V_{CC}=0V, β_F=49

V_{BC}(sat)=0.6V, V_{BE}(FA)=0.75V, V_{BE}(sat)=0.8V

R_{CI}=0.27kΩ, R_{CR}=0.3kΩ , R_E=1.24kΩ , and $R_{D,O}$=$R_{D,N}$=2kΩ

- Solution

$$\boxed{V_{OH} = V_{CC} - R_{CI}\left(\frac{V_{CC} - V_{EE} - V_{BE,BN}(FA)}{R_{CI} + (1+\beta_F)R_{D,N}}\right) - V_{BE,BN}(FA)}$$

$$\boxed{V_{OH} = 0 - 0.27\left(\frac{0+5.2-0.75}{0.27+50\times 2}\right) - 0.75 = -0.762V}$$

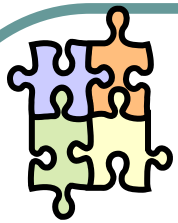
$$\boxed{V_{IL} = V_{BB} - 0.05}$$

$$\boxed{V_{IL} = -1.175 - 0.05 = -1.225V}$$

$$\boxed{V_{IH} = V_{BB} + 0.05}$$

$$\boxed{V_{IH} = -1.175 + 0.05 = -1.125V}$$

VTC of MECL I NOR/OR Gate with Output Buffer



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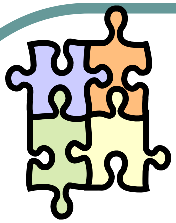
- Solution

$$V_{OL} = V_{CC} - R_{CI}\left(\frac{V_{IH} - V_{BE,I}(ECL) - V_{EE}}{R_E}\right) - V_{BE,BN}(FA)$$

$$V_{OL} = 0 - 0.27\left(\frac{-1.125 - 0.75 + 5.2}{1.24}\right) - 0.75 = -1.474V$$

$$V_S = V_I = \left(\frac{V_{CC} + V_{BC,I}(sat) + \left(V_{BE,I}(sat) + V_{EE}\right)\frac{R_{C,I}}{R_E}}{1 + \frac{R_{C,I}}{R_E}}\right)$$

$$V_S = \left(\frac{0.6 + (0.8 - 5.2)\frac{0.27}{1.24}}{1 + \frac{0.27}{1.24}}\right) = -0.29V$$



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- Solution

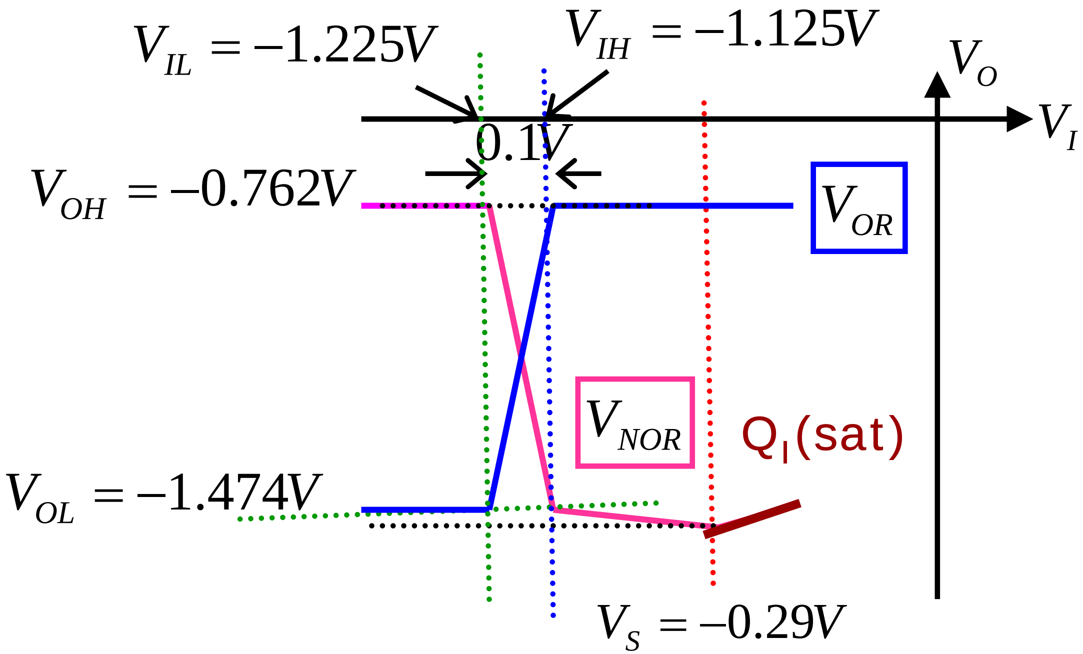
$\boxed{V_{OH} = -0.762V}$

$\boxed{V_{OL} = -1.474V}$

$\boxed{V_{IL} = -1.225V}$

$\boxed{V_{IH} = -1.125V}$

$\boxed{V_S = -0.29V}$



Fan-Out of MECL I NOR/OR Gate with Output Buffer

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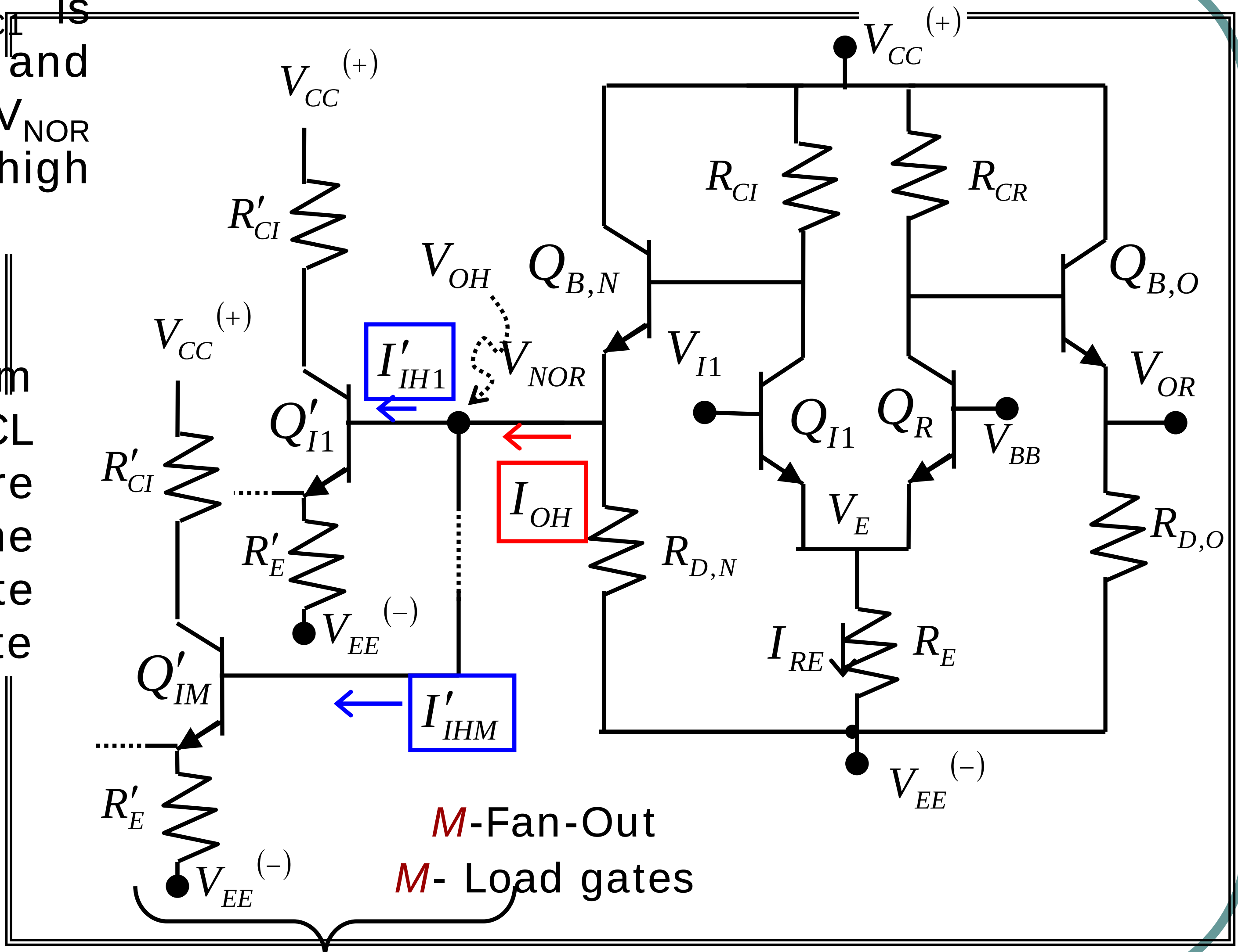
When Q_{I1} is cut- off, V_{CI} is high and therefore V_{NOR} is also high state

The maximum fan-out of an ECL is therefore dependent on the output high state of the driving gate

$$M = \frac{I_{OH}}{I'_{IH}}$$



M-Fan-Out

M- Load gates

Fan-Out of MECL I NOR/OR Gate with Output Buffer

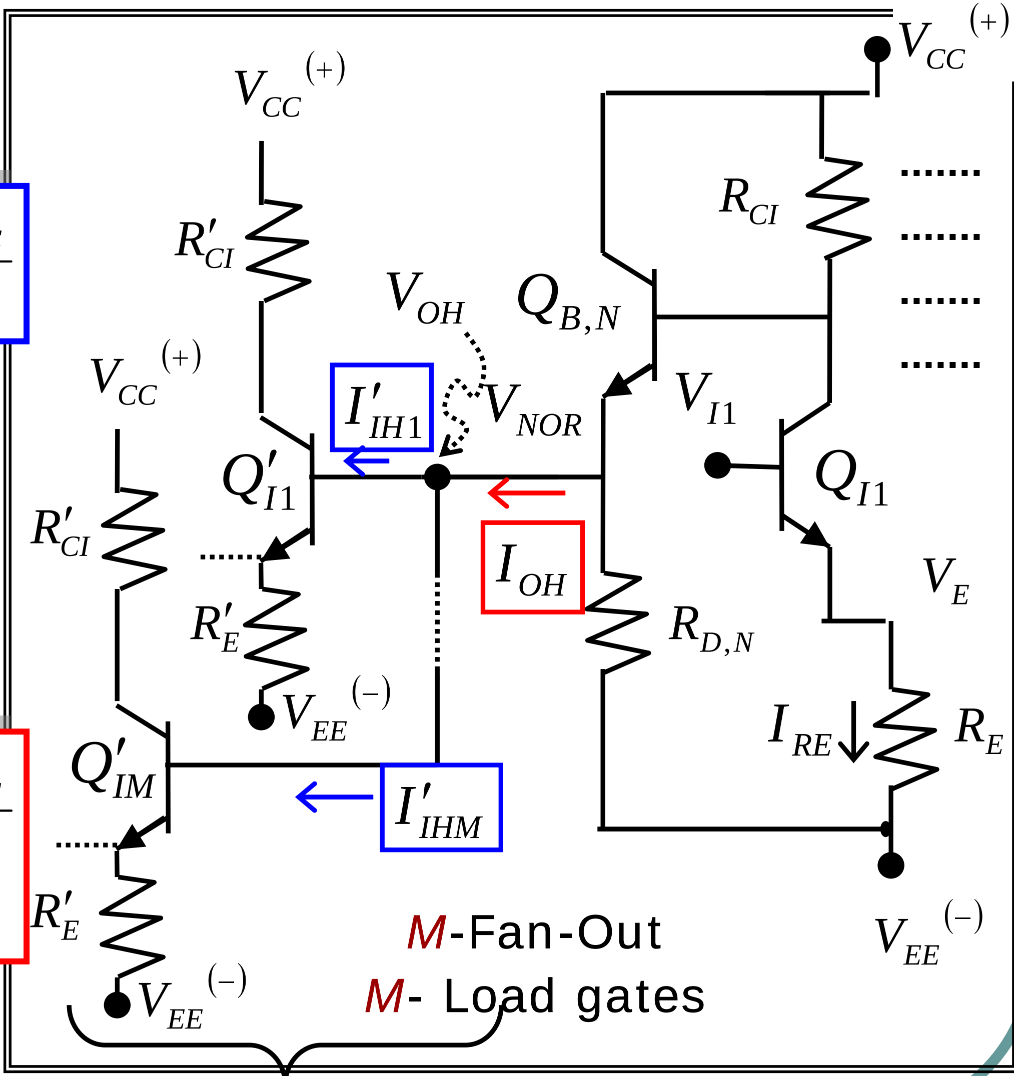
$\underline{I'_{IH}}$

$$I'_{IH} = I'_{B,I} = \frac{V_{OH} - V_{BE,I}(ECL) - V_{EE}}{(1+\beta_F)R'_E}$$

$\underline{I_{OH}}$

$$I_{OH} = I_{E,BN} - \frac{V_{OH} - V_{EE}}{R_{D,N}}$$

$$I_{OH} = \frac{V_{CC} - V_{BE,BN}(FA) - V_{OH}}{\dfrac{R_{CI}}{(1+\beta_F)}} - \frac{V_{OH} - V_{EE}}{R_{D,N}}$$



Fan-Out of MECL I NOR/OR Gate with Output Buffer

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- Example

Calculate the maximum fan-out in the last example, assuming that the load gates have reduced V_{OH} of the driving gate from -0.76V to -0.79V:

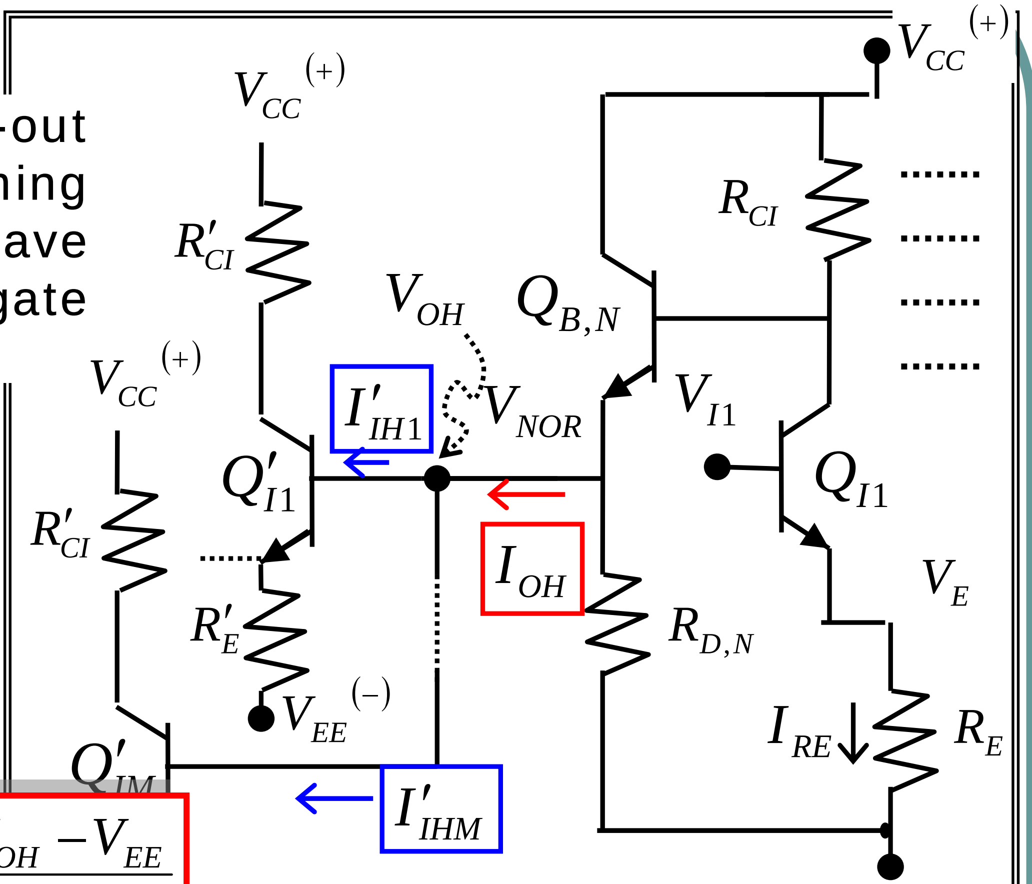
- Solution

$$I'_{IH} = I'_{B,I} = \frac{V_{OH} - V_{BE,I}(ECL) - V_{EE}}{(1+\beta_F)R'_E}$$

$$I'_{IH} = \frac{-0.79 - 0.75 + 5.2}{50 \times 1.24} = 0.059mA$$

$$I_{OH} = (1+\beta_F)\frac{V_{CC} - V_{BE,BN}(FA) - V_{OH}}{R_{CI}} - \frac{V_{OH} - V_{EE}}{R_{D,N}}$$

$$I_{OH} = 50 \times \frac{0 - 0.75 + 0.79}{0.27} - \frac{-0.79 + 5.2}{2} = 5.2mA$$



$$M = \frac{I_{OH}}{I'_{IH}} = 88$$

Power-Dissipation in MECL I circuits

Ch

Output high current supplied

$(I_{CC}(H)) + (I_{EE}(H)) + (I_{BB}(H))$

For High output, Input is <u>low</u>

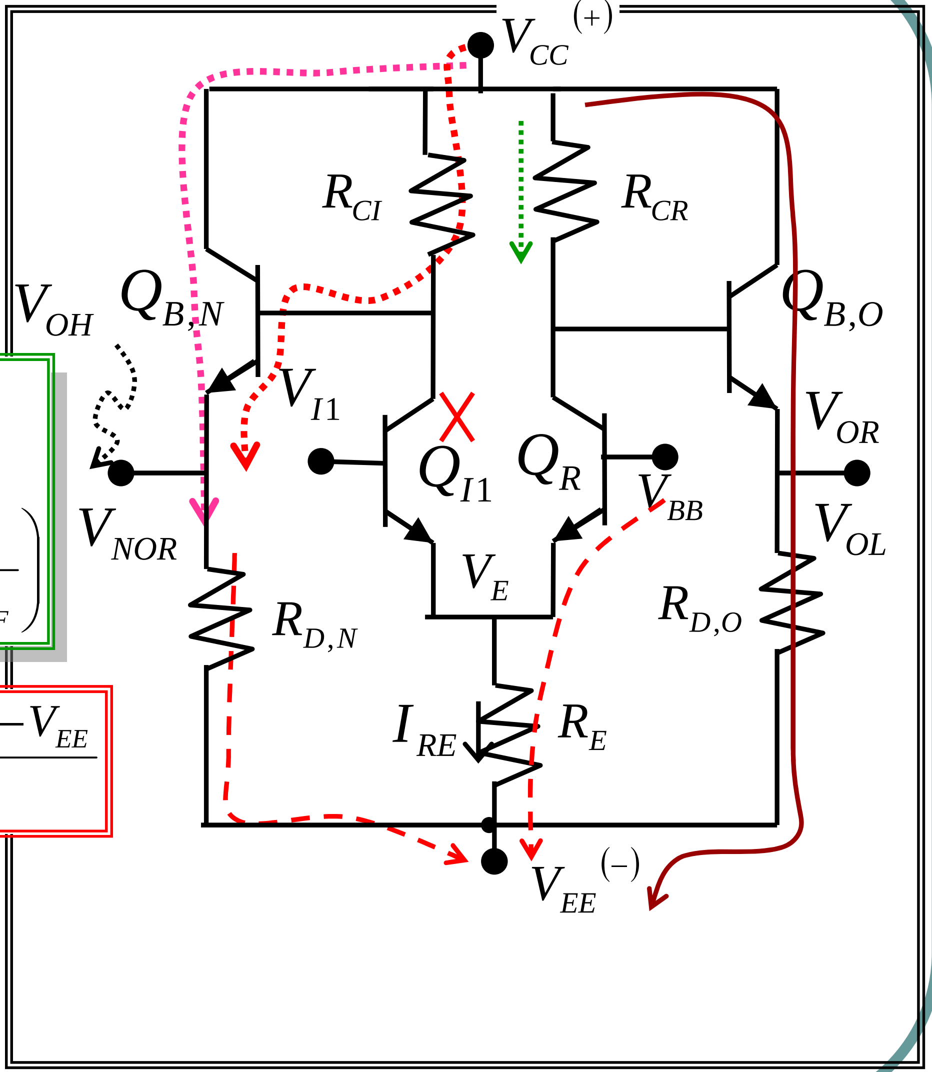
$$I_{CC}(OH) = I_{C,BN} + I_{RCI} + I_{RCR} + I_{C,BO}$$

$$I_{CC}(OH) = \frac{V_{CC} - V_{BE,BN}(FA) - V_{OH}}{R_{CI}}(1+\beta_F) + \frac{V_{CC} - V_{BE,BO}(FA) - V_{OL}}{R_{CR}} + \frac{V_{OL} - V_{EE}}{R_{D,O}}\left(\frac{\beta_F}{1+\beta_F}\right)$$

$$I_{EE}(OH) = \frac{V_{OH} - V_{EE}}{R_{D,N}} + \frac{V_{OL} - V_{EE}}{R_{D,O}} + \frac{V_{BB} - V_{BE,R}(ECL) - V_{EE}}{R_E}$$

$$I_{BB}(OH) = \frac{V_{BB} - V_{BE,R}(ECL) - V_{EE}}{(1+\beta_F)R_E}$$

Very small compared to $I_{EE}(OH)$



TTL Power-Dissipation in MECL I circuits

Ch

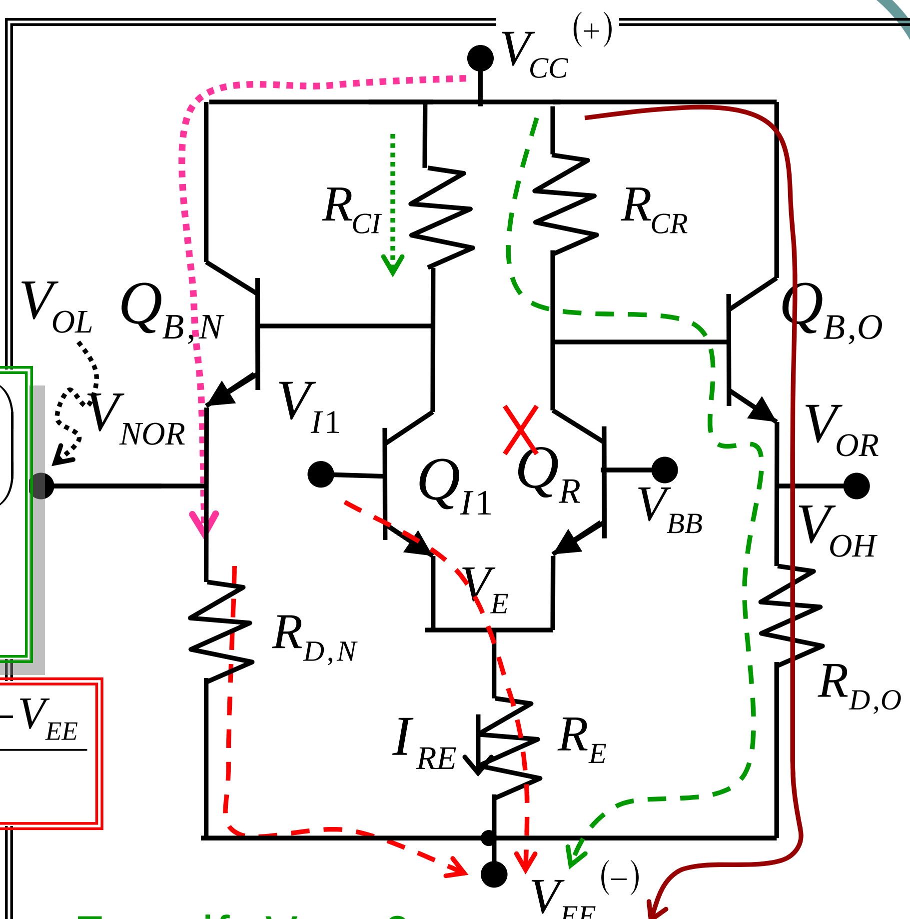
Output low current supplied
$(I_{CC}(L)) + (I_{EE}(L))$
For Low output, Input is <u>high</u>

$$\boxed{I_{CC}(OL) = I_{C,BN} + I_{RCI} + I_{RCR} + I_{C,BO}}$$

$$I_{CC}(OL) = \frac{V_{CC} - V_{BE,BN}(FA) - V_{OL}}{R_{CI}} + \frac{V_{OL} - V_{EE}}{R_{D,N}}\left(\frac{\beta_F}{1+\beta_F}\right) + \frac{V_{CC} - V_{BE,BO}(FA) - V_{OH}}{R_{CR}}(1+\beta_F)$$

$$I_{EE}(OL) = \frac{V_{OL} - V_{EE}}{R_{D,N}} + \frac{V_{OH} - V_{EE}}{R_{D,O}} + \frac{V_{IH} - V_{BE,I}(ECL) - V_{EE}}{R_E}$$

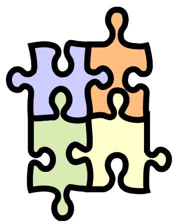
$$P_{EE}(avg) + P_{CC}(avg) = V_{EE}\left(\frac{I_{EE}(OL) + I_{EE}(OH)}{2}\right) + V_{CC}\left(\frac{I_{CC}(OL) + I_{CC}(OH)}{2}\right)$$



Zero if $V_{CC} = 0$

Power-Dissipation in MECL I circuits

Ch



- Example

Calculate the dissipated power in the driver gate for the last example

- Solution

$$I_{EE}(OH)=\frac{V_{OH}-V_{EE}}{R_{D,N}}+\frac{V_{OL}-V_{EE}}{R_{D,O}}+\frac{V_{BB}-V_{BE,R}(ECL)-V_{EE}}{R_E}$$

$$I_{EE}(OH)=\frac{-0.762+5.2}{2}+\frac{-1.474+5.2}{2}+\frac{-1.175-0.75+5.2}{1.24}$$
$$=6.723mA$$

$$I_{EE}(OL)=\frac{V_{OL}-V_{EE}}{R_{D,N}}+\frac{V_{OH}-V_{EE}}{R_{D,O}}+\frac{V_{IH}-V_{BE,I}(ECL)-V_{EE}}{R_E}$$

$$I_{EE}(OL)=\frac{-1.474+5.2}{2}+\frac{-0.762+5.2}{2}+\frac{-1.125-0.75+5.2}{1.24}$$
$$=6.76mA$$

$$P_{EE}(avg)=5.2\left(\frac{6.76+1.523}{2}\right)=35.06mW$$

Ch 11

- HW #9:Solve Problems: 11.**1-3**, 11.**08-10**, and 11.**13-19**